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(54) Planar waveguides including a lens portion

(57) Incorporating an integral lens portion constituted by a shaped volume of material of uniformly different refractive index into a planar waveguide, is not satisfactory, and instead it is common to employ geodesic lenses even though they are difficult and expensive to fabricate, and can suffer unacceptably high insertion loss. The present invention suggests an alternative lens construction; it provides an elongate planar waveguide in the form of a surface layer in a correspondingly elongate planar slab of material, the waveguide layer including a lens portion capable of modifying the wavefront of waves propagating along the waveguide, wherein the lens portion is to constructed that the effective refractive index of the layer is spatially varied in a direction approximately orthogonal to the wave propagation direction, the variation being such as to cause the required wavefront modification.

The waves guided may be mechanical, microwaves, or infra-red or visible light.

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SPECIFICATION
Waveguides

This invention concerns waveguides, and relates in particular to the formation of planar waveguides incorporating refracting elements.

The use of waveguides, devices wherein energy in wave form is confined and guided by the interfaces between media in which the phase velocity of the wave is markedly different, is now commonplace in a number of fields. Thus, waveguides are employed to channel both mechanical and electromagnetic energy—a surface acoustic wave device is an example of a waveguide for the former, while an optical fibre is one of a waveguide for the latter (and it is now quite usual to utilise waveguides for electromagnetic energy of any wavelength between the centimetre and millimetre dimensions of microwaves to the 100-nanometer dimensions of infra-red and visible light).

One particular physical form of waveguide is the elongate planar slab of material having a surface layer the refractive index of which is greater than that of the material in the body of the slab. The layer itself is the waveguide.

In a typical optical guide of the sort used in acousto-optical devices the slab body might be lithium niobate ($LiNbO_3$), and the layer might be the result of diffusing titanium atoms into the slab surface, and might be only a few microns thick. There is a need, particularly in the field of integrated optics, to be able to fabricate such planar waveguides so that they include refracting elements. It might be though that, as in conventional optics (where a light path can be modified by making the light traverse a suitably-shaped body—a lens—of a refractive index uniformly different to that of the surrounding medium, and in which the light has a corresponding different phase velocity) the waveguide could be made with an integral lens portion constituted by a shaped volume of material of uniformly different refractive index. One problem, however, is that in many cases the phase velocity of the wave in the "lens" portion of the guide can only be made slightly different from that in the surrounding region, and therefore it is difficult merely by constructing such a portion to realise lenses with sufficient power to obtain adequately short focal lengths for a given aperture. Because of this it is common, in integrated optic or acousto-optic devices such as surface interaction Bragg cells, to employ geodesic lenses, wherein a depression is machined in the surface of the substrate (prior to waveguide formation), the depression introducing additional path length which leads to focussing properties. This type of lens works reasonably well, but unfortunately is difficult, and expensive, to fabricate, and can suffer unacceptably high insertion loss. The present invention suggests an alternative lens construction that avoids the problem of the Prior Art devices and yet may be of value in the focussing of a wide variety of guided waves, ranging from mechanical surfaces acoustic waves to electromagnetic waves of a microwave, infra-red or visible light nature.

In one aspect, therefore, the invention provides an elongate planar waveguide in the form of a surface layer in a correspondingly elongate planar slab of material, the waveguide layer including a lens portion capable of modifying the wavefront of waves propagating along the waveguide, wherein the lens portion is so constructed that the effective refractive index (as defined hereinafter) of the layer is spatially varied in a direction approximately orthogonal to the wave propagation direction, the variation being such as to cause the required wavefront modification.

The expression "effective refractive index" is used herein to mean the relative phase velocity of the guided wave (relative, that is, to some defined datum value). So far as concerns electromagnetic radiation, specifically light, this may be explanded as follows. In conventional optics the refractive index n of a material is the ratio of the velocity of light *in vacuo* to that of light in the material. For the propagation of light in a layered structure containing a stratum of refractive index higher than that of its surrounding strata, the stratum can act as an optical waveguide wherein there are a discrete number of modes (including zero) which represent different transverse spatial distributions of energy in the waveguide and which can propagate without loss for theoretically ideal materials. For any given frequency the modes have differing propagation constants $\beta(2\pi/\lambda_g)$, where λ_g is the propagation wavelength of the modes in the waveguide at the given frequency ν). Defining $k(=2\pi/\lambda_o)$ as the free space wave vector for the given frequency, it follows that

$$\beta/k=\frac{\lambda_o}{\lambda_g}=\frac{v_g}{v_o}$$

where v_g is the phase velocity in the guide $(=\nu\lambda_g)$. Thus β/k is the effective refractive index of the waveguide for the given mode. By suitable design of the stratified structur it is possible to ensure that only one mode can be supported at a given frequency, so that the guide is then a single mode waveguide. Furthermore, by altering the parameters of the stratified structure—specifically, the layer thicknesses and/or the refractive indices of the strata—it is possible to alter the β/k value and thus the 'effective refractive index' of the waveguide for the given mode (this point is discussed further hereinafter).

In the case of surface acoustic waves energy flow is guided by the substrate surface. A

continuum of modes exists, and the surface wave velocity can be modified by "loading" the free surface thereby creating the mechanical equivalent of a modified refractive index.

The waveguide of the invention may be a guide for a number of different types of waves. It may, for example, guide mechanical waves (as employed in, say, a surface acoustic wave device), or it may guide electromagnetic waves (microwaves, infra-red or visible light, for instance). Though most of the remarks made herein apply to waveguides in general (regardless of what type of wave they are to guide), a few may concern specifically one or other variety—thus, for example, mechanical wave guides rather than electromagnetic wave guides, or *vice versa*.

For electromagnetic wave guides the inventive waveguide is in the form of a surface layer extending over an elongate planar slab—that is to say, it is an elongate planar slab of some suitable substrate material having extending thereover adjacent one major face thereof a thin layer of material in which the waves can propagate and that has a refractive index significantly greater than that of the substrate material (so confining the waves to the layer, whereby the layer constitutes the guide). The length of the waveguide is clearly any required to carry waves between their origin and their destination. A typical length of a planar optical device guide is 4 cms. The width is essential indefinite (it is necessary merely that it be large enough that the guide cut-off wavelength value be determined by the guide thickness). Nevertheless, a typical width for a guide in an opto-electronic device is 10 mm. The thickness of the guide is usually chosen such that the guide can support only one mode at the desired wavelength(s). The exact thickness is determined by the chosen wavelength and the refractive indices of the substrate and the guiding layer. A typical thickness for a single mode guide in an opto-electronic device is 3 microns.

Surface-layer waveguides of the type employed in this invention are themselves now quite well known. They may be made of a number of sorts of materials in a number of ways, depending on their exact purpose. Typical substrate materials for opto-electronic device guides (and, indeed, for some surface acoustic wave device guides) are glass, lithium and gallium arsenide, while the thin surface layer constituting the guide itself may be, for example, any one of: a titanium diffused layer in a lithium niobate substrate; a thin film (i.e., arsenic trisulphide) overlay of different refractive index; an ion-exchange region in a glass substrate; hetero-epitaxial layer of composition differing from that of the substrate (i.e., gallium arsenide in gallium aluminium arsenide). Where the guide layer is a "doped" version of the substrate material—for example, lithium niobate doped with titanium—it may conveniently be constructed by "diffusing" the dopant into the surface of the substrate using the conventional techniques of thermal diffusion or ion-implantation. Alternatively—and for use where the surface layer is of a material basically different to the substrate material—the layer can be formed by depositing, by evaporation perhaps, the relevant material onto the substrate surface.

The waveguide of the invention includes a portion capable of modifying the wavefront of waves propagating along the guide, which portion is referred to herein as a "lens portion" (though, as discussed below, the wavefront modification may not necessarily be a focussing or defocussing action as implied by the normal use of the word "lens"). The lens portion is an integral part of the waveguide that has itself been modified, in a manner described hereinafter, so as to have the required effect on the wavefront. The portion extends across the wave propagation direction (and beyond the extremes of the wavefronts) and along the waveguide for a length sufficient, having regard to the degree of portion modification, to have the desired refractive power effect.

The lens portion modifies the wavefront of waves propagating along the waveguide. The modification may be of any desired type, and may thus be to either or both of the shape of the wavefront and the direction of the waves. For example, the lens portion may be a prism, changing the direction of the waves by uniformly deflecting the wavefront through an angle, or the lens portion may be of positive or negative optical power, changing both the shape of the wavefront and the direction of the waves so that the waves converge to or diverge from a point along the waveguide.

The waveguide modification caused by the lens portion is the result of the effective refractive index in that part of the waveguide being spatially varied across the guide (for a lens, in a direction orthogonal to, and for a prism, in a direction approximately orthogonal to, the wave propagation direction along the guide), and the way in which this variation occurs is naturally chosen to give the wavefront modification required. A general example will suffice to illustrate this point, as follows.

One likely type of lens portion is that which causes the propagating wave to converge—to focus— at a point further along the guide, and it will usually be the case that the focus is located on the waveguide axis. So, defining the optic axis of the lens as the X-axis, and assuming that the lens portion is symmetrical about the X-axis, the effective refractive index variation $n(y)$—the index at a distance y in the Y-axis direction—will also be symmetrical about the X-axis, and will be of the form:—

$$n(y)=n_o(1+ay^2+by^4+\ldots)$$

(where n_o is the effective refractive index of the basic guide, and a and b are constants which, for a converging lens, are negative). Common choices are quadratic and quartic functions, as well as the function

$$n(y)=n_o\,\mathrm{sech}(\beta y) \qquad (1)$$

(where β is the guide propagation constant defin d earlier, and which is determined by the guide design). The final choice of grading function depends on the design requirements, acceptable aberation limits, and method of fabrication.

The distribution shown in equation (1) has a focal length, for plane parallel input waves, of

$$f=\frac{\pi}{2\beta} \qquad (2)$$

and it can be shown that, if Δn is the maximum effective refractive index difference between the lens portion of the guide and the surrounding guide material, the F-number (*F. No*) of the lens and its acceptance angle θ_{max} (relative to the X-axis) are approximately (depending on choice of acceptable aberation limits)

$$\text{F. No}=4\frac{\pi}{\sqrt{\frac{\Delta n}{n_o}}} \text{ and } \theta_{max}=\sqrt{\frac{\Delta n}{n_o}} \text{ (Assuming } \frac{\Delta n}{n_o}<<1) \qquad (3)$$

For a circular simple refracting lens (in the thin lens approximation)

$$\frac{1}{f}=\frac{2}{r}\left(\frac{\Delta n}{n_o}\right)$$

so that even at full aperture (ignoring aberation effects—which would limit the useful aperture in practical cases)

$$\text{F. No}=\frac{f}{2r}=\frac{1}{4\left(\frac{\Delta n}{n_o}\right)} \qquad (4)$$

The graded index lens of (3) thus offers a reduction in *F. No* by a factor of

$$\frac{1}{\sqrt{\frac{\Delta n}{n_o}}}$$

(approximately) when compared with a circular conventional refracting element. This is obviously a significant advantage in cases where

$$\frac{\Delta n}{n_o}<<1$$

(as in the case for Ti diffused optical in $LiNbO_3$—where

$$\frac{\Delta n}{n_o}\simeq 10^{-2})$$

and for piezoelectric shorting or mass loading effects on surface acoustic wave velocities.

The physical manner in which the effective refractive index is varied may, as noted briefly hereinbefore, involve changes either to the actual refractive index of the slab material and/or to the dimensions (specifically the height of the wav guide).

If the effective refractive index is to be varied by altering the actual refractive index, then this can conveniently be effected by injecting into the guide layer a suitable material in an amount which varies spatially across the guide in a manner appropriate to providing the desired refractive index. Inde d, most advantageously this injection stage can be coupled with the one used (if it b so) to make the guide layer in the first place. The methods used to inject the material, and to control its spatial

concentration across the guide, may b any found convenient. For exampl , if the injection process uses the technique of ion implantation then the concentration variation can be achieved by scanning the ion beam across the guide surface (in a raster pattern, perhaps), and altering the scanning sp ed (the beam dwell time), the number of scans over the same area, or the concentration of ions in the beam. If, however, the injection process uses thermal diffusion from a layer previously deposited on the guide surface, then the concentration variation can be achieved by varying the thickness of the layer in a manner corresponding to the desired diffusion concentration. In this latter case the layer of material to be diffused can itself be formed, so as to have its thickness vary across the guide, by—for example—"condensing" (or otherwise depositing) the material onto the guide surface through a variable slit shutter that opens/closes in a way suitably programmed to give the required layer thickness spatial variation. Another way of attaining the variable thickness layer is to employ a source for the material (say, from which the material is to be evaporated, then condensing onto the guide surface) having a geometrical shape such that the desired layer thickness variation results.

If the effective refractive index is, on the other hand, to be varied by modifying the effective height (thickness) of the guide layer, then this can conveniently be done simply by constructing on top of the previously-formed guide layer a surface layer whose height varies spatially across the guide in such a way that the combination of the two layers has a height (thickness) with the required spatial modification. Generally the material for this top layer will be the same as that from which the guide layer itself is formed, and it may be constructed using any acceptable method—for example, using the slit shutter or shaped source methods mentioned above.

The invention naturally extends to any waveguide device using a waveguide as described and claimed herein.

Claims

1. An elongate planar waveguide in the form of a surface layer in a correspondingly elongate planar slab of material, the waveguide layer including a lens portion capable of modifying the wavefront of waves propagating along the waveguide, wherein the lens portion is so constructed that the effective refractive index (as defined hereinafter) of the layer is spatially varied in a direction approximately orthogonal to the wave propagation direction, the variation being such as to cause the required wavefront modification.

2. A waveguide as claimed in claim 1 and for electromagnetic waves, which waveguide is an elongate planar slab of substrate material having extending thereof adjacent one major face thereof a thin layer of material in which the waves can propagate and that has a refractive index significantly greater than that of the substrate material, the thickness of the layer being such that the guide can support only one mode at the desired wavelength(s).

3. A waveguide as claimed in either of the preceding claims, wherein the lens portion is of positive or negative optical power, changing both the shape of the wavefront and the direction of the waves so that the waves converge to or diverge from a point along the waveguide.

4. A waveguide as claimed in any of the preceding claims, wherein the spatial variation of the effective refractive index across the guide is according to a quadratic and quartic function, or to the function

$$n(y)=n_o\ \mathrm{sech}(\beta y)$$

(where β is the guide propagation constant defined hereinbefore).

5. A waveguide as claimed in any of the preceding claims, wherein the physical manner in which the effective refractive index is varied involves the injection into the guide layer of a suitable material in an amount which varies spatially across the guide in a manner appropriate to providing the desired refractive index.

6. A waveguide as claimed in claim 5, wherein the injected material is so positioned and its spatial concentration across the guide controlled, by: ion implantation, scanning the ion beam across the guide surface, and altering the scanning speed, the number of scans over the same area, or the concentration of ions in the beam; or by the thermal diffusion of a layer previously deposited on the guide surface, the thickness of this layer having been varied in a manner corresponding to the desired diffusion concentration either by depositing the material onto the guide surface through a variable slit shutter that opens/closes in a way suitably programmed to give the required layer thickness spatial variation or by employing a source from which the material is to be evaporated, then condensing onto the guide surface, having a geometrical shape such that the desired layer thickness variation results.

7. A waveguide as claimed in any of the preceding claims and substantially as described hereinbefore.

8. A waveguide device using a waveguide as claimed in any of the preceding claims.

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